STATE TRANSITIONS IN LMC X-3

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Abstract

We carried out a multiwavelenght study of the black-hole candidate LMC X-3 with *XMM-Newton*. The system showed a transition to a low-hard state, in which the X-ray spectrum was well fitted by a simple power law. It then returned to a high-soft state, characterised by a strong disk-blackbody component. The line-of-sight absorption column density is $\lesssim 4 \times 10^{20}$ cm^{-2}, consistent with the foreground Galactic absorption. This rules out wind accretion. We argue that, despite LMC X-3 being a high-mass X-ray binary, Roche-lobe overflow is the main mechanism of mass transfer. From UV/optical observations in the low-hard state, we determine that the companion is a slightly evolved B5 star with a mass $M \approx 4.5$ M$_\odot$. This is indeed consistent with the secondary star being close to filling its Roche lobe.

Key words: Galaxies: individual: M83 (=NGC 5236) – Galaxies: nuclei – Galaxies: spiral – Galaxies: starburst – X-rays: binaries – X-rays: galaxies

1. Introduction

LMC X-3 (Leong et al. 1971) is a persistent X-ray source in the Large Magellanic Cloud (LMC). The orbital period is 1.705 d (van der Klis et al. 1985; van Paradijs et al. 1987). The non-detection of eclipses in the X-ray curve implies that the orbital inclination of the system is $\lesssim 70°$ (Cowley et al. 1983). Its optical brightness ($V \sim 17$) indicates that the system has a massive companion. From optical spectroscopic observations, its mass function was estimated to be $\simeq 2.3$ M$_\odot$ (Cowley et al. 1983). The inferred mass of the compact object in LMC X-3 would then be $\gtrsim 7$ M$_\odot$ (Paczyński 1983). If the effect of soft X-ray irradiation on the surface of the secondary star is taken into account, a mass function $f_{\rm M} = 1.5 \pm 0.3$ M$_\odot$ is obtained instead (Soria et al. 2001). This corresponds to a lower limit for the mass of the compact object $M_{\rm X} > (5.8 \pm 0.3)$ M$_\odot$. Thus, the system is a black-hole candidate (BHC).

2. Spectral states and mass transfer mechanism

Most BHC show transitions between soft and hard X-ray spectral states. In the soft state, their X-ray spectrum consists of a thermal component and a power-law component; in the hard state, the thermal component is insignificant and the power law is harder. The thermal component, which can be fitted by a blackbody or disk-blackbody spectrum with a temperature ~ 1 keV, is interpreted as thermal emission from the inner accretion disk. The power-law component is believed to be Comptonised emission from a disk corona (Sunyaev & Titarchuk 1980) or from the high-speed infalling plasma near the black-hole event horizon (Titarchuk & Zannias 1998). The photon index of the power law $\Gamma \approx 2.5$–4 in the soft state, and $1.5 \lesssim \Gamma \lesssim 2$ in the hard state.

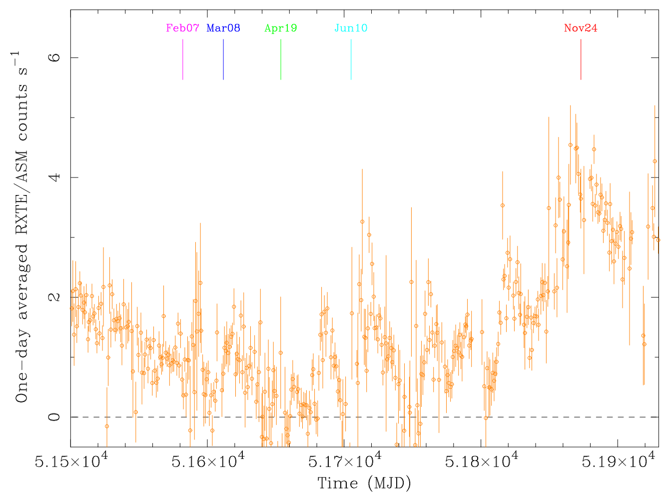

Figure 1. The time of our XMM-Newton observations of LMC X-3, marked by solid vertical lines, are plotted above the RXTE/ASM light curve.

LMC X-3 is normally found in the soft state. A rare transition to the hard state occurred in 2000 April–May (Boyd et al. 2000). Other short-duration transitions to a hard state were observed in 1997 and 1998 (Wilms et al. 2001). LMC X-1, another high-mass BHC in the LMC, has been seen in the soft state only. In contrast, Cyg X-1, the high-mass BHC in our Galaxy, tends to be in the hard state for the majority of the time.

An unsolved problem for LMC X$-$3 is the process of mass transfer. With an estimated mass of the companion star 4 M$_\odot \lesssim M_2 \lesssim 8$ M$_\odot$ (Cowley et al. 1983), the system appears to be intermediate between high-mass black-hole binaries such as Cyg X$-$1 (mass of the companion star

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Table 1. XMM-Newton EPIC-PN Observation Log

Rev.	Start–end (MJD)	Live exp. time	Mode
0066	51653.5396–51653.8475	05.8 ks	small w
0092	51705.0096–51705.2897	16.9 ks	small w
0176	51872.9600–51873.1786	09.2 ks	timing

Table 2. XMM-Newton RGS Observation Log

Rev.	Start–end (MJD)	Exp. time	Instrument
0030	51581.9517–51582.0985	12.1 ks	RGS2
0045	51611.7275–51611.8367	09.0 ks	RGS1+2
0066	51653.1377–51653.6587	44.5 ks	RGS1+2
0092	51704.2877–51705.2917	77.6 ks	RGS1+2
0176	51872.9347–51873.1786	21.0 ks	RGS1+2

≈ 33 M$_\odot$, see Giles et al. 1986), and low-mass black-hole binaries such as A0620$-$00 (mass of the companion star ≈ 0.7 M$_\odot$). In the former class of systems, mass transfer occurs mainly via a stellar wind, and the donor star is more massive than the primary; in the latter, the donor star is usually a late-type star filling its Roche lobe. We used *XMM-Newton* to study the spectral behaviour of LMC X-3 over its spectral state transition, and to determine the mechanism of mass trasfer in this system.

3. Results of our *XMM-Newton* study

LMC X-3 was observed with the European Photon Imaging Camera (EPIC), the Reflection Grating Spectrograph (RGS) and the Optical Monitor (OM) on board *XMM-Newton*, between 2000 February and November. See also Wu et al. (2001) and Soria et al. (2001). All EPIC exposures were taken with the "medium" filter; Some are affected by pile-up due to the high count rate. Here, we present only the EPIC-PN exposures not affected by pile-up (ie., those taken in "small window" and in "timing" mode; see the *XMM-Newton* Remote Proposal Submission Software Users' Manual). The log of the EPIC-PN observations used for this study is shown in Tables 1; the log of the RGS observations is listed in Table 2. The data were processed using the 5.1 version of the SAS.

The X-ray luminosity of LMC X-3 appeared to be declining during our 2000 February–March observations, with the *RXTE*/ASM $1.5 - 12$ keV count rate generally below 2 ct s^{-1} (Figure 1). The Rev0066 observation (2000 April 19) was carried out around the middle of a faint-hard state, when the *RXTE*/ASM count rate was consistent with zero. The *RXTE*/PCA data obtained on May 5.76 and 10.01 UT showed power-law spectra with a photon index 1.60 ± 0.05 and a soft (2–10 keV) X-ray flux of ≈ 5–9×10^{36} erg s^{-1} at 50 kpc (Boyd et al. 2000). The system seemed to be returning to the high-soft state at the time of the Rev0092 (June 10) observations. It was in the high-soft state during our last observation (Rev0176, November 24).

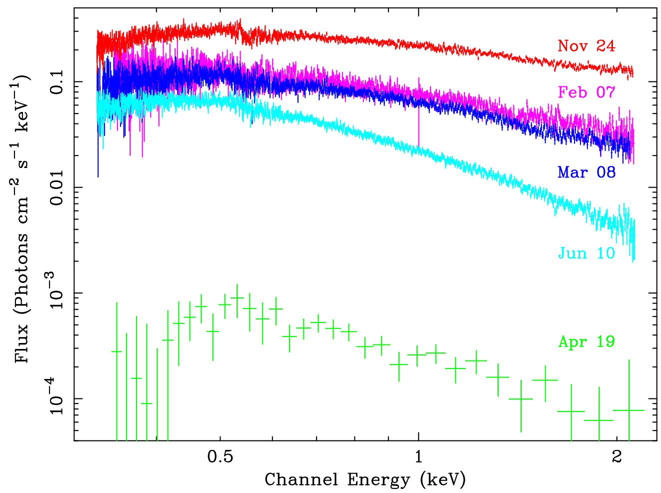

Figure 2. Unfolded XMM-Newton/RGS spectra show the transition from the high-soft to the low-hard state, and back to the high-soft state, between 2000 February and November.

Table 3. Spectral parameters of the XMM-Newton EPIC-PN observations

Date of obs	T_{in} (keV)	Γ	$L_{0.3-10}$ (erg s^{-1})
Apr 19	not detected	$1.9^{+0.1}_{-0.1}$	4.6×10^{35}
Jun 10	$0.25^{+0.01}_{-0.01}$	$1.89^{+0.02}_{-0.02}$	2.8×10^{37}
Nov 24	$1.37^{+0.01}_{-0.01}$	$2.59^{+0.05}_{-0.04}$	6.4×10^{38}

The thermal disk component disappeared in the low-hard state, but became dominant again as the system returned to the high-soft state (Table 3 and Figure 3). The emitted luminosity in the 0.3-10 keV band varied by 3 orders of magnitude, reaching $L_{\rm x} \approx 6 \times 10^{38}$ erg s^{-1} (0.3–10.0 keV band) in November 2000 (here we have assumed a total a column density $n_{\rm H} = 4 \times 10^{20}$ cm^{-2} and a distance to the LMC of 50 kpc). This is the highest X-ray luminosity ever measured for this system. The optical/UV luminosity increased by a factor of 2 (0.8 mag) in the high-soft state.

The high-resolution RGS spectra allowed us to determine the absorbing column density for the X-ray emitting region. From the depth of the O I absorption edge at 23 Å ($E = 0.54$ keV), we find a total line-of-sight column density $n_{\rm H} \lesssim 4 \times 10^{20}$ cm^{-2} (Figure 4). The foreground Galactic interstellar absorption in the direction of LMC X-3 is $n_{\rm H} = 3.2 \times 10^{20}$ cm^{-2} (Wilms et al. 2001). Hence,

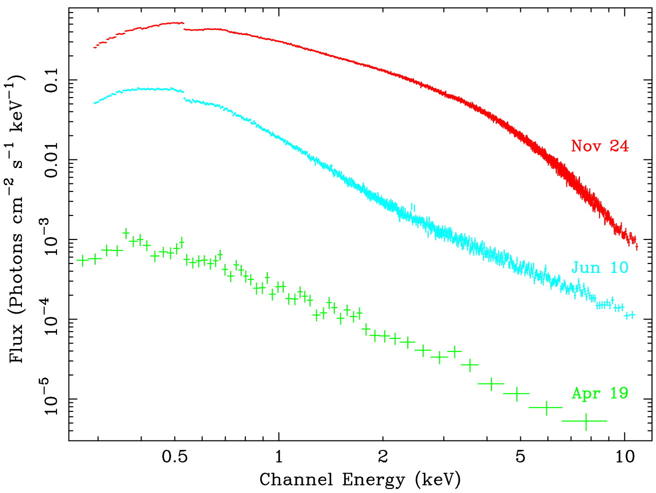

Figure 3. Unfolded XMM-Newton/EPIC-PN spectra show that the disk-blackbody component is not detected in the X-ray spectrum during the low-hard state (April 19). The spectrum in the low-hard state is a simple power-law. The disk-blackbody component becomes prominent again as LMC X-3 returns to the high-soft state.

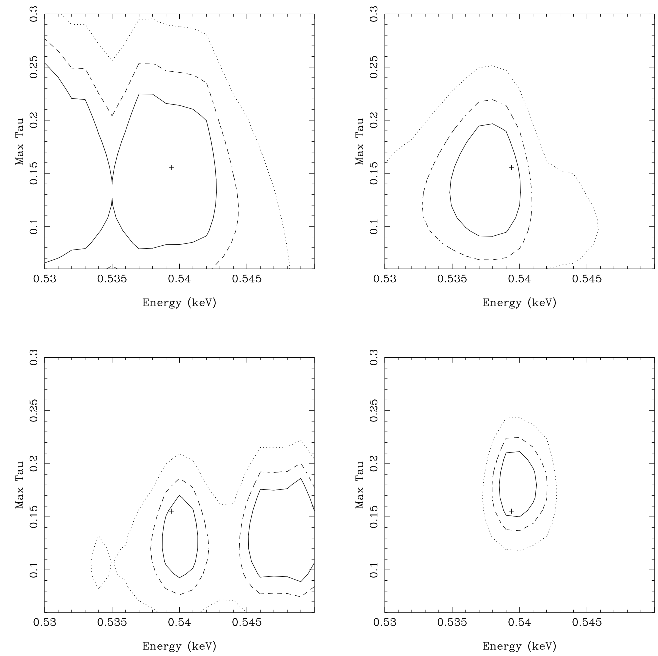

Figure 4. Results of our fitting a power law × edge model to a 3-Å region around the O I edge at 23 Å (E = 0.54 keV). The 1-σ, 2-σ and 3-σ confidence contours on the wavelength and optical depth of the edge are shown for the spectra taken in Rev. 30 (top left), 45 (top right), 92 (bottom left) and 176 (bottom right). The cross in each panel marks the best-fit parameters when all four spectra are fitted simultaneously. Each of the four separate observations is consistent with this value. We infer that the total line-of-sight absorption is consistent with the expected Galactic interstellar absorption in the direction of LMC X-3.

the intrinsic column density is $\lesssim 10^{20}$ cm^{-2}. This holds both in the low-hard and in the high-soft state, and is in contrast to the larger intrinsic column density expected for a companion with a strong stellar wind.

The non-detection of obvious emission lines in the RGS spectra also indicates the absence of wind matter ejected in previous epochs (cf. the P Cygni lines seen in Cir X-1, Brandt & Schulz 2000). Thus, the *XMM-Newton* spectral data rule out wind accretion from a massive companion. The high luminosity observed in the X-ray bands therefore requires the companion to overflow its Roche lobe.

4. Mass and spectral type of the companion star

Observations of LMC X-3 in its X-ray low state allowed us to determine the mass and spectral type of the companion. The system was observed with *XMM-Newton*/OM on 2000 April 19. We obtained an average brightness $v = 17.48 \pm 0.02$, $b = 17.39 \pm 0.02$, $u = 16.56 \pm 0.02$ in the three *XMM-Newton/OM* optical bands. Using the latest available matrix of colour transformation coefficients (SAS Version 5.1, file OM_COLORTRANS_0005.CCF), we find that this corresponds to $V = 17.48 \pm 0.03$, $B = 17.36 \pm 0.03$, $U = 16.79 \pm 0.03$. This implies a temperature 15500 $\lesssim T_{\rm eff} \lesssim$ 16500 and a spectral type B5 (Figure 5; see also Soria et al. 2001). Hence, we infer that the companion is a slightly evolved star of mass $4.5 \lesssim M_2 \lesssim 5.0$ M$_\odot$. No significant wind is expected from such a star, in agreement with the low column density inferred from the X-ray data.

It has been suggested (Cowley et al. 1983; Negueruela & Coe 2002) that the companion is a main sequence B3 or B2.5 star ($M_2 \gtrsim 7$ M$_\odot$). Such a star could also have the observed absolute magnitude $M_V = -1.21 \pm 0.16$ but would have much higher bolometric luminosity and temperature (bluer colors). However, their observations were carried out when the surface of the companion star was stronly heated by the X-ray source, and are therefore less reliable than our *XMM-Newton*/OM observation for a spectral classification.

The mean mass density in the Roche lobe of the companion star is uniquely determined by the binary period (Frank et al. 1992):

$$\rho \equiv \frac{3M_2}{4\pi R_{\rm L}^3} \approx 115 P_{\rm hr}^{-2} \approx 0.069 \text{ g cm}^{-3}. \quad (1)$$

We plot in Figure 6 the evolutionary tracks in the (M_V, ρ) plane for a typical LMC metallicity $Z = 0.008$ (eg, Caputo et al. 1999), compared with the mean density inside the Roche lobe. The dashed line corresponds to a radius of $0.95R_{\rm L}$. Stars with a mass $M \approx 4.5$ M$_\odot$ would be very close to filling their Roche lobe. Hence, mass transfer would occur mainly via Roche lobe overflow, in agreement with our X-ray observations. A more massive companion would not fill its Roche lobe. In particular, a B3V companion would only fill less than half of the volume of its

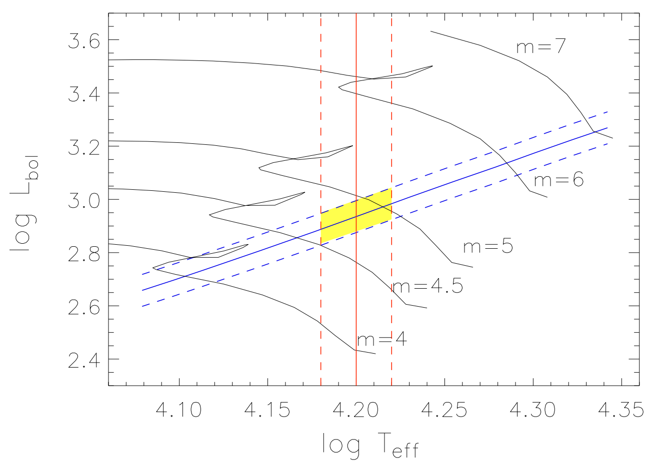

Figure 5. The evolutionary tracks for stars of various masses, at Z = 0.008, in the ($\log T_{\rm eff}, \log L_{\rm bol}$) plane, show the acceptable range of temperatures and luminosities derived from our XMM-Newton/OM observations. Masses are in units of solar mass, $M_\odot = 1.99 \times 10^{33}$ g; temperature is in K; luminosity is in units of solar bolometric luminosity, $L_{\rm bol,\odot} = 3.9 \times 10^{33}$ erg s^{-1}. The observed colours constrain the temperature range (red lines). The observed brightness constrains the bolometric luminosity, as a function of temperature (blue lines).

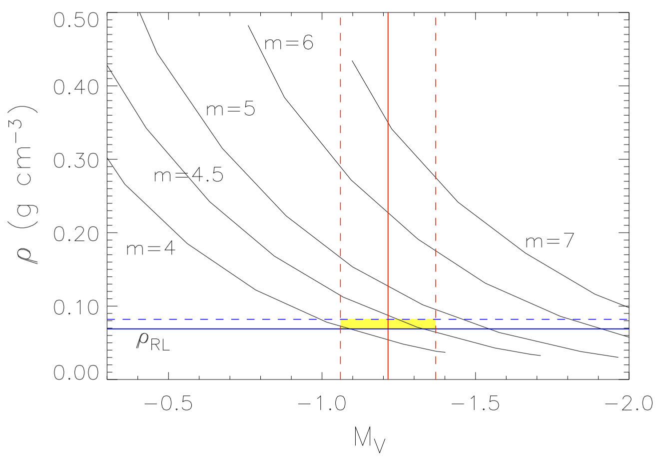

Figure 6. We compare the mean density inside the RL of the secondary star ($\rho = 0.069$ g cm^{-3}, derived from the binary period) with the density of stars of various masses, in the (M_V, ρ) plane (evolutionary tracks from Girardi et al. 2000, assuming Z = 0.008). The dashed horizontal line corresponds to a radius $R = 0.95 R_{\rm L}$ for which Roche-lobe overflow becomes significant. Only masses $M \lesssim 4.5\ M_\odot$ are consistent with the observed brightness $M_V = -1.21 \pm 0.16$.

Roche lobe. In that case, the mechanism of mass transfer would have to be a stellar wind. This is ruled out by the UV/optical colours and by the low column density inferred from the RGS data.

5. Conclusions

We have shown that the X-ray spectrum of LMC X-3 in the low-hard state is consistent with a simple power law. As the system returns to the high-soft state, the disk-blackbody component (interpreted as emission from an accretion disk) becomes more prominent. The luminosity in the low-hard state was $L_{\rm x} \approx 5 \times 10^{35}$ erg s^{-1} (0.3–10.0 keV band). In the high-soft state, $L_{\rm x} \approx 6 \times 10^{38}$ erg s^{-1}, higher than the Eddington luminosity limit of an accreting neutron star, and consistent with the classification of LMC X-3 as a BHC.

The low line-of-sight column density, even at such a high luminosity, rules out wind accretion from a massive companion, and requires that mass is transferred via RL overflow. In turns, this implies that the companion star is close to filling its RL.

We have shown that the optical/UV brightness and colours of the companion star suggest that it is a slightly evolved B5 star of mass $M_2 \approx 4.5$ M$_\odot$, rather than a main-sequence B3 star as previously thought. We have also shown that an evolved B5 companion would fill its RL, while a main-sequence B3 companion would not.

Acknowledgements

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